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Method for Manufacturing a Buried Tunnel Junction in a
Surface-emitting Semi-conductor Laser

The invention relates to a method for manufacturing a buried tunnel junction in a surface-emitting semi-conductor laser and a laser of this type.

Surface-emitting laser diodes (in English: Vertical-Cavity Surface-Emitting Laser or VCSEL) are semi-conductor lasers, in which the light emission occurs perpendicular to the surface of the semi-conductor chip. Compared to conventional edge-emitting laser diodes, the surface-emitting laser diodes have several advantages such as low electrical power consumption, the possibility of direct checking of the laser diode on the wafer, simple coupling options to the glass fiber, longitudinal single mode spectra and the possibility of interconnection of the surface-emitting laser diodes to a two-dimensional matrix.

In the field of fiberoptic communications technology - because of the wavelength dependent dispersion or absorption - there is the need for VCSELs in a wavelength range of approx. 1.3 to 2 μm , in particular around the wavelengths of 1.31 μm or 1.55 μm . Long-wave laser diodes with application-competent properties, especially for the wavelength range above 1.3 μm , have been produced to date

using InP-based connection semiconductors. GaAs-based VCSELs are suitable for the shorter wavelength range of $< 1.3 \mu\text{m}$. To date the following approaches to solving this problem have been pursued:

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A continuous-wave VCSEL, which emits with a power of 1 mW at $1.55 \mu\text{m}$ is, for example, constructed of an InP-substrate with metamorphic layers or mirrors (IEEE Photonics Technology Letters, Volume 11, Number 6, June 1999, pp. 629 - 631). A
10 further proposal relates to a VCSEL emitting continuously at $1.526 \mu\text{m}$, which is produced using wafer connection of an InP/InGaAsP-active zone with GaAs/AlGaAs mirrors (Applied Physics Letters, Volume 78, Number 18, pp. 2632 to 2633 of April 30, 2001). A VCSEL with air - semi-conductor mirror
15 (InP - air gap DBRs, for distributed Bragg reflectors) is proposed in IEEE ISLC 2002, pp. 145 - 146. In this case, a tunnel contact [viz. tunnel junction] is applied between the active zone and the upper DBR mirror, whereby a current limitation is achieved by undercutting the tunnel contact
20 layer. The air gap surrounding the remaining tunnel contact zone is used for wave guidance of the optical field.

In addition, it is well known from the publication on the occasion of the 26th European Conference on Optical
25 Communication, ECOC 2000, "88 °C, Continuous-Wave Operation of $1.55 \mu\text{m}$ Vertical-Cavity Surface-Emitting Lasers", a VCSEL with antimonide-based mirrors, in which an undercut InGaAs active zone is enclosed by two n-doped InP layers, at which AlGaAsSb DBR mirrors abut.

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The optimum properties with regard to output, operating temperature range and modulation bandwidth are exhibited, however, by VCSEL with buried tunnel contacts (English: buried tunnel junction, BTJ). The production and structure of the buried tunnel junction will be presented hereinafter with reference to Figure 1. Using molecular beam epitaxy (English: molecular beam epitaxy, MBE) a highly doped p⁺/n⁺ layer pairing 101, 102 is produced with minimal band separation. The actual tunnel junction 103 is formed between these layers. Using reactive ion etching (English: reactive ion etching, RIE) a circular or ellipsoid zone is formed, which is formed essentially by the n⁺-doped layer 102, the tunnel junction 103 and part of or the entire p⁺-doped layer 101. This zone is covered in a second epitaxy passage with n-doped InP (layer 104), so that the tunnel junction 103 is "buried". The contact [viz. junction] zone between the covered layer 104 and the p⁺-doped layer 101 acts as a boundary layer when a voltage is applied. The current flows through the tunnel junction with resistances of typically $3 \times 10^{-6} \Omega \text{ cm}^2$. In this fashion, the current flow can be restricted to the actual zone of the active zone 108. In addition, heat production is low, because the current flows from a high-ohmic p-doped to a low-ohmic n-doped layer.

The overgrowth of the tunnel junction results in slight variations in thickness, which act unfavorably on the lateral wave guiding, so that occurrence of high lateral modes is facilitated, especially in the case of larger apertures. Therefore, only small apertures can be used with less corresponding laser power for single mode operation -

especially required in glass fiberoptic communication technology. A further drawback of this concept is the required double epitaxy, which is required for overgrowth of the buried tunnel contact. In analogy with the GaAs-based short-wave VCSELs, a production process with only one epitaxy - for yield and cost considerations - would be of considerable advantage.

Examples and applications of VCSELs with buried tunnel junctions can be found, for example, in "Low-threshold index-guided 1.5 μm long wavelength vertical-cavity surface-emitting laser with high efficiency", Applied Physics Letter, Volume 76, Number 16, pp. 2179 - 2181 of April 17, 2000; in "Long Wavelength Buried Tunnel Junction Vertical-Cavity Surface-Emitting Lasers", Adv. in Solid State Phys. 41, 75 to 85, 2001; in "Vertical-cavity surface-emitting laser diodes at 1.55 μm with large output power and high operation temperature", Electronics Letters, Volume 37, Number 21, pp. 1295 - 1296 of October 11, 2001; in "90 °C Continuous-Wave Operation of 1.83 μm Vertical-Cavity Surface-Emitting Lasers", IEEE Photonics Technology Letters, Volume 12, Number 11, pp. 1435 to 1437, November 2000 and in "High-speed modulation up to 10 Gbit/s with 1.55 μm wavelength InGaAlAs VCSELs", Electronics Letters, Volume 38, Number 20, September 26, 2002.

In the following, on the basis of the construction of the buried tunnel junction described in Figure 1, the structure of the InP-based VCSEL presented in the aforementioned

literature will be explained briefly with reference to Figure 2.

The buried tunnel junction (BTJ) is arranged in reverse in this structure, so that the active zone 106 is placed above the tunnel junction with the diameter D_{BTJ} between the p⁺-doped layer 101 and the n⁺-doped layer 102. The laser beam exits in the direction indicated by the arrow 116. The active zone 106 is surrounded by a p-doped layer 105 (InAlAs) and a n-doped layer 108 (InAlAs). The facial side mirror 109 over the active zone 106 consists of an epitaxial DBR with some 35 InGaAlAs/InAlAs layer pairs, whereby a reflectivity of approximately 99.4 % results. The posterior mirror 112 consists of a stack of dielectric layers as DBR and is closed off by a gold layer, whereby a reflectivity of almost 99.75 % results. An insulating layer 113 prevents the direct contact of the n-InP layer 104 with the p-side contact layer 114, which is generally comprised of gold or silver (in this context see DE 101 07 349 A1).

The combination comprised of the dielectric mirror 112 and the integrated contact layer 114 and the heat sink 115 results in a significantly increased thermal conductivity compared to epitaxial multi-layer structures. Current is injected via the contact layer 114 or via the integrated heat sink 115 and the n-side contact points 110. Express reference is again made to the literature cited above for further details relating to the production and properties of the VCSEL types represented in Fig. 2.

The object of the invention is to propose in particular an InP-based surface-emitting laser diode with buried tunnel junction (BTJ-VCSEL), which can be produced more economically and in higher yield. In addition, the lateral single-mode operation should be stable even with larger apertures, whereby an overall higher single-mode output is made possible. The method according to the invention for producing a buried tunnel junction in a surface-emitting semi-conductor laser, which has a pn-transiton with an active zone surrounded by a first n-doped semi-conductor layer and at least one p-doped semi-conductor layer and a tunnel junction on the p-side of the active zone, which borders on a second n-doped semi-conductor layer, provides for the following steps: In a first step the layer intended for the tunnel junction is laterally ablated by means of material-specific etching up to the desired diameter of the tunnel junction, so that an etched gap remains, which surrounds the tunnel junction. In a second step, the tunnel junction is heated in a suitable atmosphere until the etched gap is closed by mass transport from at least one semi-conductor layer bordering on the tunnel junction. The semi-conductor layers bordering on the tunnel junction are the second n-doped semi-conductor layer on the side of the tunnel junction facing away from the active zone and a p-doped semi-conductor layer on the side of the tunnel junction facing the active zone.

It is particularly advantageous for the aforementioned mass transport technique (MTT), if at least one of the aforementioned semi-conductor layers bordering on the tunnel

junction is comprised of a phosphide compound, in particular InP.

5 The present invention solves both the problem of double epitaxy and that of the built-in lateral wave guide through the use of the aforesaid mass transport technique. Thus, the MTT replaces the second epitaxy process and thereby avoids the otherwise lateral thickness variation that occurs, with the consequence of a strong lateral wave guide. Burying the
10 tunnel junction no longer occurs by overgrowth but by undercutting the tunnel junction layer and then closing the etched zone by means of mass transport from adjacent layers. In this way, surface-emitting laser diodes can be produced more economically and in higher yields. In addition, lateral
15 single-mode operation is stabilized even with larger apertures, which results in higher single-mode performance.

The mass transport technique was utilized in another context in the early 80s for producing buried active zones for the
20 so-called buried heterostructure (BH) laser diodes based on InP (see "Study and application of the mass transport phenomenon in InP", Journal of Applied Physics 54(5), May 1983, pp. 2407 - 2411 and "A novel technique for GaInAsP/InP buried heterostructure laser fabrication" in Applied Physics
25 Letters 40(7), April 1, 1982, pp. 568 - 570). The method was, however, found to be unsatisfactory because of considerable degradation problems. This degradation of the laser produced by means of MTT is due to the erosion of the lateral etched flanks of the active zone, which cannot be adequately
30 qualitatively protected by MTT. Express reference is made to

the aforementioned literature citations for details and implementation of the mass transport technique.

It has been found that the aforementioned aging mechanism in the mass transport technique, which obstructed realization of usable BH lasers, does not play a role in the imbedding of tunnel junctions, because in these there is no highly excited electron-hole-plasma as in an active zone of the laser and consequently surface-emitting combinations that cause the degradation problems, do not occur.

The invention of the mass transport VCSELs (MT-VCSEL) makes it possible to produce technically simpler and better - in terms of the maximum single-mode performance - longwave VCSELs, especially on an InP basis.

The mass transport process is carried out preferably in a phosphor atmosphere comprised of H_2 and PH_3 , for example, during heating of the component. The preferred temperature range is between 500 and 800 °C, preferably between 500 and 700 °C. An option in the mass transport technique is in treating the wafer with H_2 and PH_3 in a flowing atmosphere during heating to 670 °C and then holding at this temperature for an additional period (total treatment duration is about one hour). Experiments with InP layers in a hydrogen atmosphere also resulted in a mass transport of InP.

Because of the mass transport process the etched gap closes and thus buries the tunnel junction. Owing to the high band separation of InP and the low doping, the zones adjacent to

the tunnel junction and closed by the mass transport do not represent tunnel junctions and therefore block the current flow. On the other hand, these zones contribute substantially to thermal dissipation because of the high thermal conductivity of InP.

For producing a surface-emitting laser diode according to the invention it is advantageous to start with an epitaxial initial structure, in which, sequentially, a p-doped semiconductor layer - which is applied on the p-side of the active zone, the layer intended for the tunnel junction and then the second n-doped semi-conductor layer are applied, wherein initially a circular or ellipsoid stamp is formed by means of photolithography and / or etching (reactive ion etching (RIE), for example), whose flanks enclose the second n-doped semi-conductor layer and the layer provided for the tunnel junction perpendicular to the layer and extend at least to below the tunnel junction layer, and that then the undercutting according to the invention of the tunnel junction layer and the burying of the tunnel junction by means of mass transport is done.

The structure obtained in this fashion is ideally suited for producing surface-emitting laser diodes.

In another embodiment of the invention, a further semiconductor layer is provided, which communicates on the p-side of the active zone at the second n-doped semi-conductor layer at which the side of the tunnel junction is facing away from the active zone. This additional semi-conductor layer itself

borders on a third n-doped semi-conductor layer, wherein this further semi-conductor layer is also initially ablated by means of material-selective etching laterally up to a desired diameter and then heated in a suitable atmosphere until the etched gap is closed by mass transport from at least one of the n-doped semi-conductor layers adjacent to the additional semi-conductor layer.

In this connection, it is advantageous if the lateral material-selective etching and the mass transport process is done at the same time as the corresponding production according to the invention of the buried tunnel junction.

If a material - such as, for example, InGaAsP - is used for the additional semi-conductor layer that is different from that of the tunnel junction - such as, for example, InGaAs - advantage can be taken of a different lateral etching, whereby the lateral wave guide as defined by the diameter of the additional semi-conductor layer can become wider than the active zone, whose diameter corresponds to the diameter of the tunnel junction. This embodiment thus makes possible a controlled adjustment of the lateral wave guide that is separate from the current aperture. For this purpose this additional semi-conductor layer is not arranged in a node but in an antinode (maximum) of the longitudinal electrical field.

The band gap of the additional semi-conductor layer should be larger than that of the active zone, in order to prevent optical absorption.

A wet chemical etching process using $\text{H}_2\text{SO}_4:\text{H}_2\text{O}_2:\text{H}_2\text{O}$ etching solution in a ratio of 3:1:1 to 3:1:20 has been shown to be advantageous for material-selective etching, if the tunnel
5 junction is comprised of InGaAs, InGaAsP or InGaAlAs.

A buried tunnel junction in a surface-emitting semi-conductor produced according to the method of the invention has a number of advantages: In comparison to previous solutions to
10 the overgrowth of the tunnel junction using a second epitaxy process, only one epitaxy process is now necessary and consequently the laser diodes are more economical and can be produced with higher yields. When using InP for the mass transport process, the lateral zones enclose the tunnel
15 junction, which block the current flow laterally from the tunnel junction and at the same time contribute appreciably to thermal conduction into the adjacent layers. In addition, a surface-emitting semi-conductor according to the invention has only a very low built-in wave guide, which facilitates
20 stabilization of the lateral single-mode operation even with larger apertures and thus overall higher single-mode performances result than in the previous solutions.

A surface-emitting semi-conductor laser according to the
25 invention is described in Claim 11; advantageous embodiments are described in the respective dependent claims. The respective advantages of this surface-emitting semi-conductor were described essentially with the portrayal of the method according to the invention. Other advantages and embodiments

of the invention will become more obvious from the following exemplary embodiments. Where:

5 Figure 1 is a diagrammatic representation of a buried tunnel junction in prior art surface-emitting semiconductor lasers;

10 Figure 2 is a diagrammatic representation of a cross-section through a prior art surface-emitting semiconductor laser with buried tunnel junction (BTJ-VCSEL);

15 Figure 3 represents a diagrammatic cross-sectional view of a typical epitaxial initial structure for a mass transport VCSEL (MT-VCSEL) according to the invention;

 Figure 4 represents the structure of Fig. 3 with the formed stamp;

20 Figure 5 represents the structure of Fig. 3 with a more deeply formed stamp;

25 Figure 6 represents the structure according to Fig. 4 after undercutting of the tunnel junction layer;

 Figure 7 represents the structure according to Fig. 6 after the mass transport process;

30 Figure 8 represents a diagrammatic cross-sectional view of a MT-VCSEL according to the invention;

Figure 9 represents an improved embodiment of an epitaxial initial structure, and

5 Figure 10 represents a diagrammatic cross-sectional view of a further embodiment of the invention.

In the introduction to the description, production and structure of a buried tunnel junction and a surface-emitting
10 laser diode having the type of tunnel junction according to Fig. 1 or 2 were described. In the following, embodiments of the invention will be explained in more detail with reference to Fig. 3 to 10.

15 Fig. 3 diagrammatically represents a typical epitaxial initial structure for a MT-VCSEL according to the invention. Starting with the InP substrate S and in sequence a n-doped epitaxial Bragg mirror 6, an active zone 5, an optional p-doped InAlAs layer 4, a p-doped bottom InP layer 3, a tunnel
20 junction 1 comprised of at least one each of a high p- and n-doped semi-conductor layer, which is situated in a node (minimum) of the longitudinal electrical field, a n-doped upper InP layer 2 and a n⁺-doped upper contact layer 7 are deposited.

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Then, by means of photolithography and etching, circular or ellipsoid stamps are produced on a wafer having the initial structure according to Fig. 3. The stamps are shown in cross-section in Fig. 4 and 5. They extend at least to underneath
30 the tunnel junction 1, which has a thickness d (see Fig. 4)

or to the lower p-InP layer 3 (Fig. 5), whereby an edge 3a is etched into this lower layer 3. The stamp diameter ($w + 2h$) is typically approx. 5 to 20 μm larger than the aperture diameter w provided of typically 3 to 20 μm , such that h is approx. 3 to 10 μm . In this connection h (see Fig. 6) represents the width of the under cut zone B of the layer provided for the tunnel junction 1.

Now, as shown in Fig. 6, the tunnel junction 1 is ablated laterally by means of material-selective etching, without etching the layers - here the n-doped upper InP layer 2 and the p-doped lower InP layer 3 - surrounding it. The lateral undercutting of the tunnel junction 1 (or the layer intended for the tunnel junction) of typically $h = 2$ to 10 μm is used for defining the aperture A, which corresponds to the remaining tunnel contact area. The material-selective etching is, for example, possible using wet chemistry with using $\text{H}_2\text{SO}_4:\text{H}_2\text{O}_2:\text{H}_2\text{O}$ etching solution in a ratio of 3:1:1 to 3:1:20, if the tunnel junction 1 is comprised of InGaAs, InGaAsP or InGaAlAs.

In order now to obtain a buried tunnel junction 1 having the structure shown in Fig. 6, the gap etched according to the invention, that is, the zone B laterally surrounding the tunnel junction 1 is closed by means of a mass transport process. In this case, the wafer having the structure shown in Fig. 6, is heated under a phosphoric atmosphere for some time preferably at 500 to 600 $^{\circ}\text{C}$. Typical times are 5 to 30 minutes. During this process, small amounts of InP are moved

from the upper and / or lower InP layer 2 or 3, respectively into the previously etched gap, which as a result closes.

The result of the mass transport process is shown in Fig. 7.
5 The transported InP in the zone 1a now closes the tunnel junction 1 laterally (buries it). Because of the high band separation of InP and the low doping, the zones 1a do not represent tunnel junctions and therefore block the current flow. Accordingly the zone crossed by current of the active
10 zone 5 having the diameter w (see Fig. 6) corresponds substantially to the area (aperture A in Fig. 6) of the tunnel junction 1. On the other hand, the annular zones 1a comprised of InP and having the annular width h contribute, because of the high thermal conductivity of InP,
15 substantially to the thermal dissipation via the upper InP layer 2.

The further processing of the structure according to Fig. 7 to obtain the finished MT-VCSEL corresponds to the technique
20 well-known from the BTJ-VCSELs, as they are described in the beginning and in the cited literature and will not be described in more detail here. Fig. 8 shows the finished MT-VCSEL according to the invention. In this case, an integrated gold heat sink referenced using 9, 8 designates a dielectric
25 mirror, which borders on the upper n-doped InP layer 2 and is surrounded by the gold heat sink 9, 7a designates the annular structured n-side contact layer and 10 is an insulation and passivation layer composed of, for example, Si_3N_4 or Al_2O_3 , which protects both the p-doped lower and the n-doped upper
30 InP layer 3, 2 from direct contact with the p-side contact 11

or the gold heat sink 9. The p-side contact 11 is produced using Ti/Pt/Au, for example. 12 designates the n-side contact made of Ti/Pt/Au, for example.

5 In this connection is noted that the active zone 5, which is shown here as a homogeneous layer, is comprised generally of a layer structure of 11 thin layers, for example (5 quantum film layers and 6 barrier layers).

10 An improved embodiment of the epitaxial initial structure is represented in Fig. 9, wherein an additional n-doped InP layer 6a is inserted underneath the active zone 5. This layer reinforces the lateral thermal drainage from the active zone 5 and accordingly reduces its temperature.

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Another embodiment of the invention is shown in Fig. 10. Here the mass transport technique is applied in two overlying layers, wherein preferably a single mass transport process is implemented both for the tunnel junction layer and for the
20 additional semi-conductor layer 21. In Fig. 10 this additional semi-conductor layer 21 is arranged above the tunnel junction 1. The additional semi-conductor layer 21 borders on two n-doped InP layers, 2, 2'. The zone 20 laterally encompassing the additional semi-conductor layer 21
25 consists of InP, which has reached into the previously undercut zone 20 in virtue of the mass transport and closes the same.

Insofar as the index of refraction of the additional semi-
30 conductor layer 21 differs from the surrounding InP, this

layer 21 generates a controlled lateral wave guide. For this purpose this layer is not arranged in a node but in an antinode (maximum) of the longitudinal electrical field. When using different semi-conductors such as, for example, InGaAs for the tunnel junction 1 and InGaAsP for the additional semi-conductor layer 21, a different lateral etching can be used, whereby the lateral waveguide, which is defined by the diameter of the layer 21, becomes wider than the active range of the active zone 5, whose diameter is equivalent to the diameter of the tunnel junction 1. This embodiment thus makes possible a controlled adjustment of the lateral wave guide that is separate from the current aperture.